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Key Gaps for Enabling Plant Growth in Future Missions

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Growing plants to provide food or psychological benefits to crewmembers is a common vision for the future of human spaceflight, often represented in media and in serious concept studies. The complexity of controlled environment agriculture, and plant growth in microgravity have and continue to be the subject of dedicated scientific research. However, actually implementing these systems in a way that will be cost effective, efficient, and sustainable for future space missions is a complex, multi-disciplinary problem. Key questions exist in many areas: human medical research in nutrition and psychology, horticulture, plant physiology and microbiology, multi-phase microgravity fluid physics, hardware design and technology development, and system design, operations and mission planning. This paper describes key knowledge gaps identified by a multi-disciplinary working group within the National Aeronautics and Space Administration (NASA). It also begins to identify solutions to the simpler questions identified by the group based on work initiated in 2017.

One of the first challenges in a collaborative conversation on plant growth research is defining the context for the project. Initial experiments have provided food the crew can consume almost as a novelty. Small scale systems, even in continuous operation and sized for daily or weekly consumption, are unlikely to provide a substantial caloric contribution to the crew diet. Variety in the diet and other psychological benefits may mean that they could still play an important role in a food system for a long duration mission. They could also provide a role as a nutritional supplement for key nutrients. This supplemental “pick-and-eat” type system was key focus for discussion. In larger scales the plants could be a primary contributor to calories and nutrients. An entirely vegan diet is possible, but designing a vegan diet that would be acceptable to the crew from plants that can be easily grown would be a complex challenge. In some studies plants are even considered as part of diets with fish or other animals within closed environments. The working group agreed that the most important near-term goals were enabling near-term demonstration of plants as a reliable contributor to a food system, which means smaller quantities and microgravity compatible systems for the International Space Station (ISS) and cis-lunar demonstrations to supplement a stored food system. However, these systems should be designed so that they could evolve into larger scale systems that provide a substantial calorie contribution to the diet and reduce the amount of stored food provided. Entirely vegan diets or diets with plants and locally raised fish or meats were interesting research topics, but would not be the focus of system development and demonstration.

When considering the key knowledge gaps for these systems, many of these questions are related to environment, either natural or induced. Many issues are from the natural environment in microgravity, or radiation. Others are part of the microbiome environment that we are only beginning to understand.

These include synergies between the plants and beneficial microbes (*both bacteria and fungi*) in the rhizosphere and phyllosphere of plants, and the positive and negative changes to the spacecraft microbiome that occur from sustained closed environmental, which could potentially include the introduction of new types of pathogens. Induced environment questions include the effects of contaminants from plants on conventional life support trace gas control systems, or concerns about the effect residual biocides commonly used in spacecraft systems might have on plants.

Answering questions on microgravity fluid flow will require activities that bridge the gap from pure scientific research to applied research. A review of previous experiments illustrates many phenomena that are relevant to fluid flow and control (water and oxygen) to plant roots. A list of experiments were identified that will focus on key questions to examine passive versus active systems, and soil media, hydroponic, or aeroponic approaches to water delivery. The system design must consider many different gravity environments if the early "pick-and-eat" demonstrations and operations are to be relevant to larger systems. Eventually, the largest plant growth systems would be expected to be in use on planetary surfaces in a partial gravity environment. Thus, the microgravity compatible designs should take into account how they could evolve to operation in a gravity field to enable the most reuse of knowledge from system experience. The bulk of the biological research conducted on the plants would be conducted on Earth, and the most useful results will come from matching the conditions as closely as possible to the spacecraft system environment.

Studying the induced environment brings up many options, since it could be changed depending on design cost trades, or hard constraints from some system component. Multiple questions involving integration with the life support system were identified. Questions about how the plants impact the life support system may be easier to answer than questions about how systems impact the plants. For example, a short set of calculations is proposed to show the impact of closed versus open growth chambers on the crew habitat thermal system. But water fed to the plants is more complex. Can the plants survive the presence of a biocide in the crew's potable water supply? Will it accumulate in edible biomass and be harmful to the crew in large quantities? If biocide is not acceptable, how can the water system be designed to provide the water the plants need yet not have a system fouled by biofilm development? These questions require tests that include growing multiple kinds of plants in multiple conditions, with the sort of repetition required for statistical significance in biological experiments. These tests will inherently take time.

Despite all these open research questions, plants have successfully been grown in space in multiple systems. Many of these have been research tools, but the crews have also been able to eat plants in space from Russian and US systems. The most recent NASA activities have utilized the VEGGIE unit on ISS. But there is a substantial difference between demonstrating that plants can survive in space, and demonstrating that they can be a reliable component of a food and life support system. Using the VEGGIE system for food production for the crew required new levels of integration with the crewmembers. This emphasized additional challenges, like food safety, that will have system impacts. Additionally, the experience re-emphasized the challenges of microgravity fluid management. But it has successfully produced food for crew consumption multiple times, and thus is a proven model showing the basic feasibility of food production that NASA intends to reuse over the life of ISS. However, it was never intended as the model for large scale food production, and new designs could provide substantial improvements.

Significant constraint are a fundamental part of the equation in any spacecraft system design. Mission duration and autonomy, volume, and power are the most basic requirements which drive development activities. Studies of equivalent system mass have been used to identify the highest priority upgrades that would be needed for next generation systems. The obvious place to make improvements would be in the hardware for the plant growth system itself. Minimizing mass and power consumption is important for all spacecraft systems. However, early results suggest that the overall habitat design and volume efficiency per plant may be the most important driver. Additional opportunities to incorporate automation, robotics, or teleoperation could reduce crew operations but may add infrastructure. Identification of key parameters for surface versus transit growth scenarios may lead to different design considerations for different gravity levels.

The properties of the plants grown are also a critical consideration. The first step is to carefully select the plants that provide the best nutritional impact and naturally provide the best productivity for the resources provided. Engineered biology and genetic modifications provide new tools to manipulate the plants themselves to achieve the best results within the system mass, volume, and power available. Opportunities exist to tailor plants for the space environment, helping to improve yield, stress tolerance, and potentially areas such as nutrition and food safety.

As the plant system grows, other technologies may be required within the spacecraft. Food safety, cooking, waste processing, and providing nutrients to the plants will all ultimately be part of a successful food production system.

Envisioning future spacecraft and exploration missions is often one of the most enjoyable parts of a career in aerospace, but designs must be data driven to know whether they are providing improvements to the state of the art. Identifying key knowledge gaps will lead to defining what ground and flight tests can help to address these gaps to feed information to future system design efforts. This framework could help NASA and other interested communities evolve from research capabilities to a true operational system.